Policy Focus

Biochar projects for mitigating climate change: an investigation of critical methodology issues for carbon accounting

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Biochar is a potential tool in our fight against climate change, driven by its high carbon stability and supported by its roles in bioenergy and soil fertility. We consider methodology aspects of biochar systems used for carbon management and investigate the criteria for establishing additionality, baselines, permanence, leakage, system drivers, measurement, verification, economics and development for successful stand-alone projects and carbon offsets. We find that explicitly designing a biochar system around 'true wastes' as feedstocks combined with safe system drivers could minimize unwanted land-use impacts and leakage. Applying baselines of biomass decomposition rather than total soil carbon is effective and supports a longer crediting period than is currently standard. With biochar production introduced into bioenergy systems, under a renewable biomass scenario, the change in emissions increases with higher fuel use, instead of decreasing. Biochars may have mean residence times of over 1000 years, but can be accounted for more effectively using a recalcitrant and labile fraction.

Interest in **biochar** as a tool to fight climate change has led to the exploration of how biochar projects might use the stabilization of biomass carbon into carbon-rich biochar, while capturing energy for mitigating climate change [1–6]. While greatly reducing our use of fossil fuels must be our primary focus, 'safe levels' of CO_2 in the atmosphere are thought by some to be lower than even present-day values, requiring significant draw-down of CO_2, in which biochar might play a part [7]. In order for biochar systems for climate change mitigation to be developed, we must devise a methodology to evaluate how much carbon a biochar project could sequester over an appropriate timescale (permanence) and determine best practices for application to systems such as the Kyoto Protocol's Clean Development Mechanism (CDM) [8]. This paper takes a step toward this task by reviewing some key methodological issues for implementation of biochar in climate change-mitigation projects, considering additionality and baseline establishment, permanence, leakage, measurement and verification, economics and development issues.

Biochar projects & carbon markets

Biochar is a carbon-rich organic material that results from the heating of biomass in the absence, or under a limited supply of oxygen. This process is known as '**pyrolysis**' and it has been used to produce charcoal as a source of fuel for millennia [9,10]. Recently, interest has grown in understanding the potential of this process to improve soil health by adding biochar as an amendment to soil, in order to manage agricultural and forestry wastes, generate energy and store carbon [11]. Biochar is included in the spectrum of black carbon materials – the name 'biochar' is used here to distinguish it from charcoal created for fuel, and to denote its particular application in carbon-sequestering and emission-reducing projects as a soil amendment. A very wide range of methods can be used to produce biochar, from systems such as the industrial biochar production system, to biomass-fuelled cook stoves that produce biochar as well as heat for cooking [12].

Carbon offsets are based on the principle of efficiency in addressing climate change. In general, emissions are to be reduced at their source. However, for efficiency and

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Key terms

Biochar: Carbon-rich organic material produced using pyrolysis.

Pyrolysis: Heating of biomass in the absence, or under a limited supply, of oxygen. Pyrolysis is used to produce biochar and energy products.

flexibility reasons, agents operating in a carbon-constrained environment are usually allowed to acquire carbon offsets (or allowances). These assets are bought when marginal abatement costs at the emissions source exceed the market price for an offset (or allowance). Compliance offset markets exist as a part of carbon regulation schemes, where offset mechanisms allow parties with emissions reduction targets (caps) to meet a portion of their targets by purchasing or trading emission credits that are generated through the implementation of greenhouse gas (GHG)-reducing projects outside the regulated regime. The most well-known offset mechanism is the CDM under the Kyoto Protocol [201]. At the same time, a significant 'voluntary carbon market' has developed alongside the compliance market, driven by businesses interested in corporate responsibility or by individuals who compensate for their personal footprint of GHGs, for example, when taking an aeroplane flight.

Since offsets basically increase the overall volume of emissions allowed to be emitted systemwide, if strict additionality is not ensured, their availability can potentially provide a misleading sense of security and simply postpone the fundamental changes that are necessary to effectively mitigate climate change. We do not make a case for or against offsets here [13–16], instead we emphasize that the need to stop our reliance on fossil fuels is of foremost importance in the fight against climate change, before offsets and other solutions. There is no reason that biochar projects must be applied within an offsetting system – they could be applied to mitigate climate change directly – but many of the basic principles of offsetting must be included when evaluating whether a biochar project should be recommended.

Within a biochar project, emissions reductions (ERs) could come from changing fresh organic matter to a much more stable form of carbon through the production of biochar, from increasing soil carbon stocks upon biochar application, possible reductions in soil emissions of GHGs, enhanced carbon storage in growing crops and decreases in fertilizer and other energy-intensive agricultural inputs (Figure 1) [1,4,17]. In addition, impacts that are directly related to avoided emissions associated with the substitution of fossil fuel by bioenergy created during the pyrolysis process could be counted. In the case of a cook-stove system, for example, reductions would come from higher stove efficiencies, resulting in lower total biomass gathering for fuel use and cleaner cooking heat production, resulting in lower GHG emissions per unit of fuel used. An industrial biochar system, on the other hand, could also derive credits from replacing fossil fuels with a renewable biomass fuel source.

To date, no biochar-specific methodologies have been approved. The biggest step needed before biochar projects can generate carbon assets, which could be used as offsets, is the development of methodologies to account for the specific impacts of biochar's application to soils and sequestration, since this is where biochar projects are unique.

Principles of carbon accounting for biochar projects

There are a number of factors that are necessary to successfully create a carbon asset in climate change mitigation projects [18–20]. We will not provide a review of all of these here, but, rather, investigate key aspects of a selection of those with particular implications for biochar projects: additionality and baseline establishment, permanence, leakage, measurement and verification, economics and development issues, with a view to establishing a framework for a methodology used to produce carbon assets from biochar projects. We focus on the aspects of carbon management specific to carbon in biochar because, although many biochar-producing systems would reduce GHGs through displacement of fossil fuels or energy efficiency, methodologies for making such measurements are better established than those for biochar, which are largely nonexistent. There are many other non-GHG-related potential impacts of biochar's application to soils and variability in these impacts due to different feedstocks and production conditions [21–24], which would need to be considered and standardized for any successful biochar project; however, these are not the focus of this paper.

Additionality & baseline establishment

If an offset project is being used as justification for emissions to continue elsewhere, we must be convinced that the project differs from the business-as-usual scenario – for example, legal regulations would not have required the changes during the lifetime of the project anyway – that is, the project is 'additional'. The CDM's 'additionality tool' is the most prominent method of establishing the additionality of a project [25]. As long as there are financial or other barriers to its implementation and it is not yet common practice, a project may be deemed additional [23]. With regard to additionality, biochar projects may have an advantage. Since they are currently uncommon technologies and not widespread methods of biomass management or energy production, one may argue that they would not have occurred without carbon sequestration as a driver. However, because there may be numerous cobenefits [21,22,26,27], if these are deemed sufficient to push the development of biochar systems without carbon finance, then additionality would need to be re-addressed.

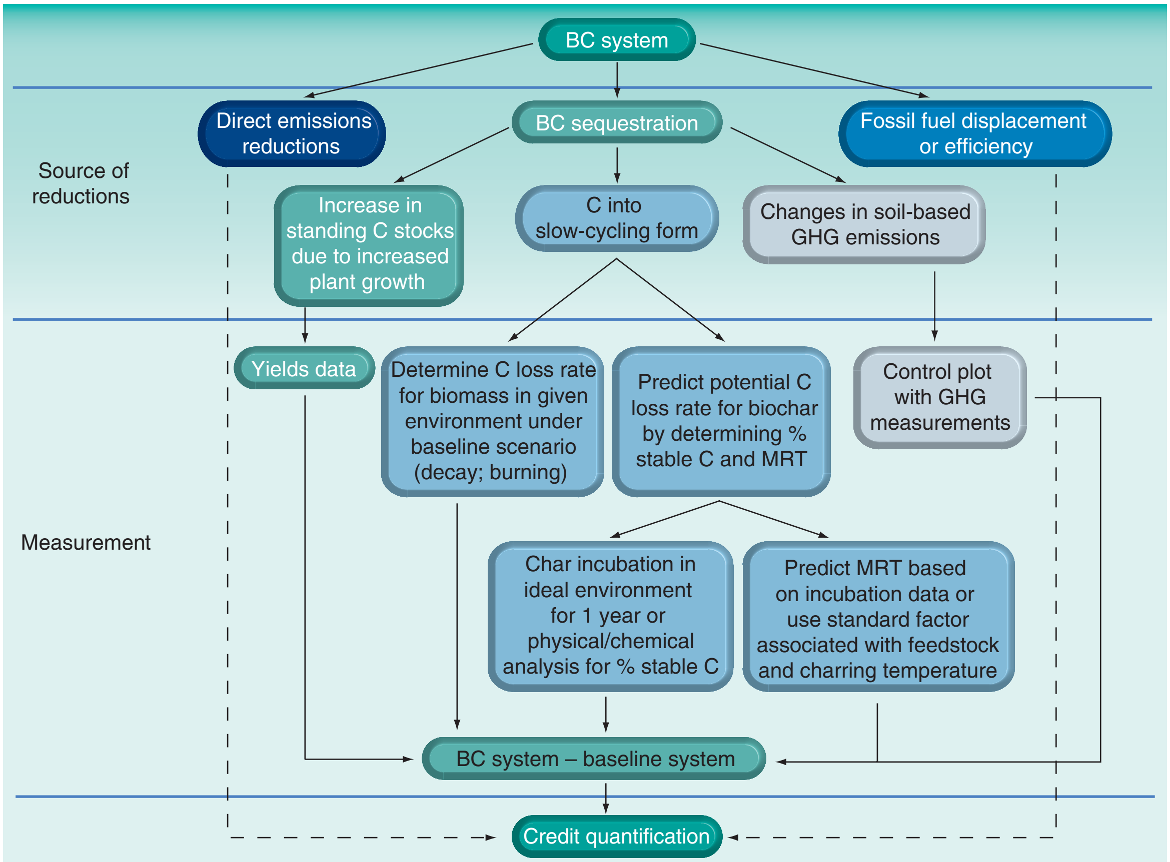

Figure 1. Potential measurement scheme for biochar-based carbon credits.
BC: Biochar; GHG: Greenhouse gas; MRT: Mean residence time.

Emissions reductions are established by predicting what would have happened if the project were not implemented (i.e., the baseline scenario) and then comparing this to what does ensue (i.e., the 'with-project scenario'). The establishment of baselines can be challenging, owing to the counterfactual reasoning involved and the challenges in predicting natural systems or economic and technological development over many years. This challenge is one of the primary reasons that offsetting projects have a limited duration, known as a 'crediting period', during which they can deliver credits, sometimes with the option for review and renewal after the first crediting period. Under the CDM, forestry projects have longer durations, owing to the longer timeline needed for effects of terrestrial sequestration to become apparent and to incentivize longer term forest rotation periods [28].

Biochar fits into this space in a complex way – most biochar projects would include standard energy-based emission reductions. Shorter crediting periods related to energy projects might apply to these components. In addition, unlike most forestry projects, much of the carbon sequestration of biochar is immediate: once the biochar is created and added to the soil, the increase in carbon stocks is established. However, the baseline to which this carbon stock would be compared could be part of a slower-cycling natural system, so a longer timeline is necessary to fully capture the impact of biochar, depending on what biomass is being used as a feedstock and what would have happened to it otherwise (Figure 2). This approach is necessary to avoid the issues outlined by Searchinger *et al.*, who point out that biomass energy's 'carbon neutrality' is not *de facto*, but, rather, highly contingent on the baseline scenario and land use effects of fuel being collected [29].

To illustrate the effects of the slower dynamics of terrestrial carbon on baseline comparisons, we consider the carbon in:

- A living tree;
- An equivalent amount of fresh dead woody biomass left to decay;
- Fresh, dead herbaceous plant mass left to decay;
- The amount of biochar that could be produced from the same mass of biomass.

Key term

Mean residence time: Average amount of time that something remains within a given system. It is used here to indicate the average time it takes before biochar carbon is mineralized to CO_2.

The living tree, depending on what stage it is at in its life cycle, will continue to grow and accumulate carbon, up to a point where it stabilizes. Fresh woody biomass is modeled as decaying at a constant rate, to the point where it takes decades for it to completely disappear, while fresh herbaceous biomass decays more rapidly [30,31]. The exact rate is highly contingent on moisture, temperature and plant species, among other factors. The rapid plant decay rate could also be considered to simulate the immediate carbon loss by burning. Biochar is modeled in two pools [32], with a recalcitrant fraction of 0.8 [1,33], which has a mean residence time (MRT) of 500 years [34], while the labile fraction (0.2) has an MRT of 15 years, assuming a relatively rapid turnover.

The first message from Figure 2 is that the chosen baseline scenario is very important. The amount of carbon maintained by biochar is immediately greater than the fresh decaying herbaceous biomass or burned biomass, but will never be higher than a living tree. The figure does not represent a system in which a new tree springs up to take the place of the one harvested (renewable biomass), and it would clearly be a mistake to consider harvesting a growing tree to 'sequester' its carbon as biochar. The second message underlines the importance of the chosen timescale. While charring herbaceous biomass is almost immediately better than leaving it to decay, the initial loss of carbon from the biochar conversion leaves less carbon than if woody biomass had just been left to decay naturally, over the first decade or two, depending on the relative rates of decay. Taking a feedstock approach to the baseline, as described here and suggested by Sohi *et al.* forces us to consider what the fate of the feedstock biomass would have been without the production of biochar, while it would be easier to ignore the feedstock source if only a total soil carbon measurement approach is used [22].

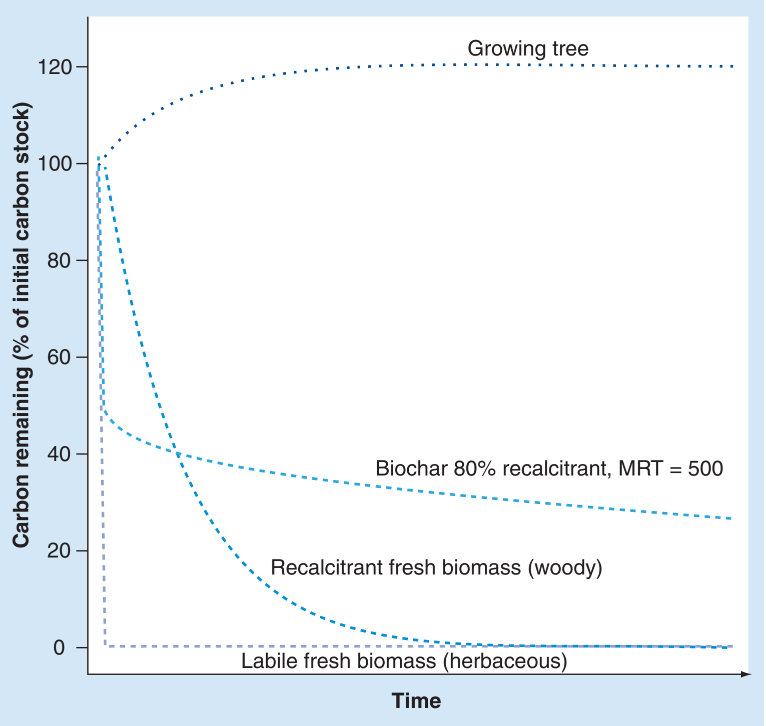

Figure 2. Alternative scenarios for biomass carbon dynamics. Each curve represents the fate of an equivalent mass of organic matter.
MRT: Mean residence time.

For projects where biomass fuel use is decreased, such as with improved cook stoves, a critical factor in establishing the baseline and the number of carbon offsets to be awarded is the estimation of the fraction of nonrenewable biomass (fNRB) from which the fuel comes (i.e., being harvested faster than it is growing back) [35,202]. As depicted in Figure 3, if the fuel source is renewable, then burning less of it is not going to differ significantly from the baseline scenario (the biomass eventually decomposes and carbon is released as CO_2) – only reductions in non-CO_2 emissions are counted (one could argue that the fuel source's living carbon stock would increase, rather than just stabilize; however, conservative methodologies make the assumption that these reductions do not count toward offsets). If the improved cook-stove project reduces the use of wood fuel harvested unsustainably, all emissions count as reductions.

In the following, this principle is applied to the case of biochar systems replacing biomass burning for energy, such as with cook stoves (Figure 4). The baseline scenario is that 6.21 t wood/year is gathered and burned in a traditional manner, producing 1.69 tCO_2-equivalent emissions (tCO_2e)/t wood of GHG if the wood is gathered unsustainably, and 0.15 tCO_2e/t wood if the wood is gathered sustainably. The first project scenario is an improved and more fuel-efficient system that uses between 90 and 15% of the wood used in the baseline scenario (open burning). Of this, 50% of the biomass is combusted and produces 1.65 tCO_2e/t wood if the gathering is unsustainable, or 0.06 tCO_2e/t wood under sustainable harvesting practices (emission factors based on Kyoto gases in Johnson *et al.* [36]), while 50% is turned into biochar (we consider the biochar to be 100% stable, for the purposes of illustrating this point). The second project scenario is an improved system that does not produce biochar and that combusts the same amount of fuel as the biochar-producing system would, minus the amount that remains as biochar, which is used to compare both systems roughly based on their energy production. If the biomass is harvested sustainably, then

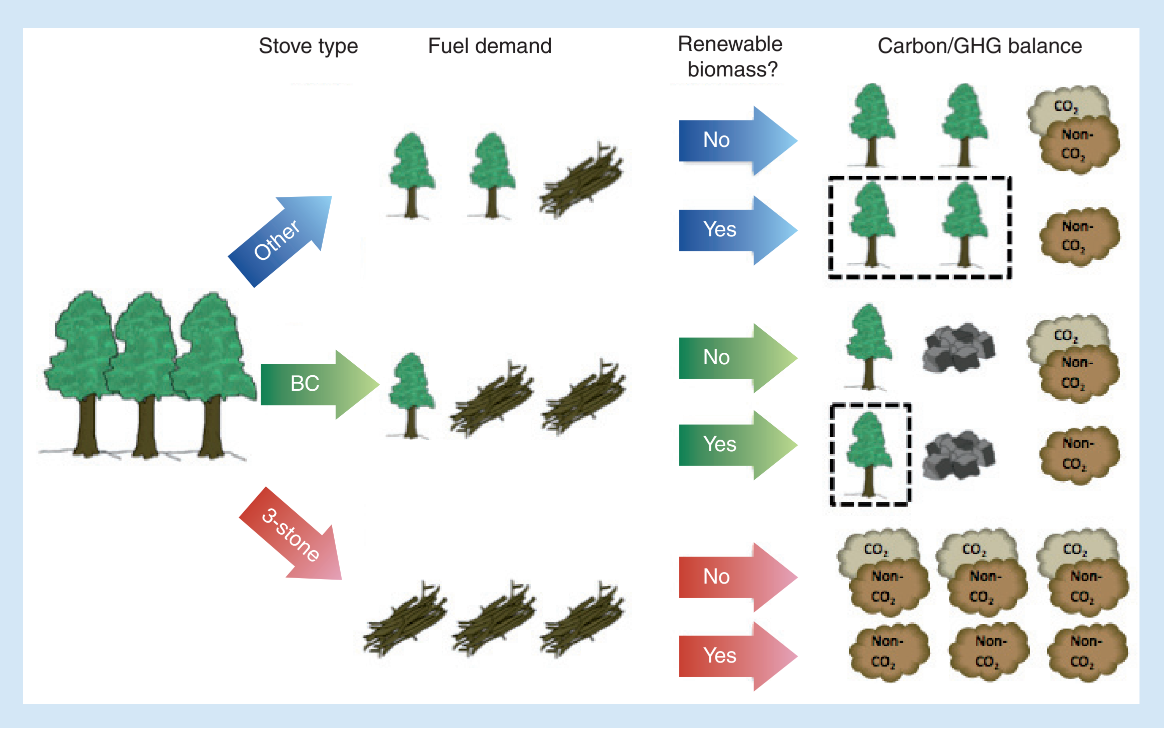

Figure 3. Climate change impact of three types of improved cook stoves (other improved, biochar producing and traditional three-stone). The impact of each stove is considered when all fuel is renewable biomass and when all fuel is nonrenewable biomass. Dashed boxes represent carbon stocks that are not included in the carbon/GHG balance.
BC: Biochar; GHG: Greenhouse gas.

any carbon in produced biochar counts as sequestered CO_2. If the biomass is harvested unsustainably, carbon in biochar is not considered to be a change from baseline. This approach is used because, even though biochar would be more stable than fresh biomass in the long term, promoting unsustainable harvests to produce biochar would be problematic because there are many critical noncarbon benefits of sustaining living biomass stocks.

As seen in Figure 4, introducing a biochar system to a region where fuel biomass is nonrenewable provides the greatest impact and, therefore, the estimation of fNRB for the baseline scenario is critical. The less fuel the system requires, the greater the reductions, as with renewable biomass. The biochar-producing system can use more total fuel and result in the same impact as a system that does not produce biochar, because the portion of fuel that is turned into biochar produces few emissions. This is at least partially offset by the fact that a biochar system would need relatively more fuel than a nonbiochar system to produce the same amount of energy, which is not considered here in detail. Interestingly, if biochar is being produced in a renewable fuel system, the more fuel that is used, the greater the sequestration impacts. Thus, in renewable systems, while nonbiochar systems rely on reductions coming from marginal differences in non-CO_2 gases, biochar-producing systems have the advantage of the renewably produced biochar, making the value of a biochar cook-stove project somewhat less dependent on the fNRB baseline.

Permanence

Should biochar carbon sequestration or a portion of the carbon sequestered be considered 'permanent'? When we manipulate the natural cycling of carbon, this can be complicated. The most common example is afforestation: if trees are planted to sequester carbon and the associated offset credit is sold, a subsequent forest fire will release the sequestered carbon, nullifying the offset. Different methods of reducing emissions or sequestering carbon have advantages and disadvantages when it comes to permanence (Table 1), and all depend significantly on the baseline scenario.

Since biochar is an organic substance, it is still part of the natural carbon cycle. Biochar is degraded by microbial as well as abiotic processes [34,37,38]. Although it is difficult to make generalizations about many of biochars' properties because it can be formed from many different feedstocks and applied to soils under diverse environmental conditions, in general, the decay of biochar

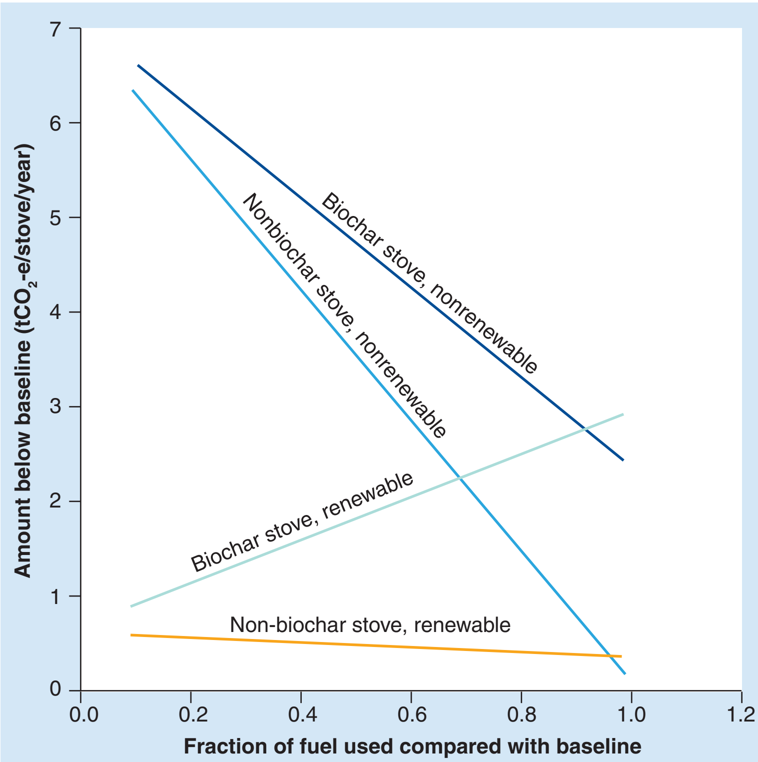

Figure 4. Potential deviation from baseline scenario (i.e., traditional three-stone cook stove) for improved cooking stoves with and without biochar in renewable and nonrenewable biomass systems. Parameters were chosen to show trends, not precise values.

takes place much more slowly than uncharred organic matter – MRTs for charred organic matter have been estimated to range between hundreds to thousands of years [34,39–45]. In some cases, shorter MRTs in the order of years to decades have been estimated, particularly in short-term studies [46,47]. The range of MRTs across biochars is related in part to different production conditions (particularly temperature) [10,34], but also potentially to the heterogeneity of biochars [35]: biochar is composed of a range of different compounds [22,48–50], some of which are more labile than others and others that are highly recalcitrant. Thus, it is necessary to develop ways of predicting a given biochar's stability. This characterization could be more easily achieved in industrial-scale systems, but may be challenging for biochars produced in less uniform systems, such as cook stoves, for which greater sampling efforts would have to be made to describe an 'average' biochar.

A first-step approximation to understanding biochar stability may be to use a two-pool model, where biochar is modeled as having a relatively labile fraction and a recalcitrant fraction [32], which could account for some of the range in measured MRTs between short- and long-term incubations. We investigate how varying the stable fraction in a two-pool model and varying the decomposition rate affect carbon storage in **Figure 5**.

Considering first the effect of varying MRT, we see in **Figure 5** that a biochar with an 80% recalcitrant fraction and a MRT of 100 years would show decomposition of 86% of the sequestered carbon within 200 years,whereas a biochar with a MRT of 500 years would lose only 34%. Thus, on a carbon-crediting timescale, MRTs of a few hundred years may suffice to provide effective permanence for a large fraction of the biochar's carbon. Within the modeled range of 20–100% stable fraction and 100–1000 MRT, we see that on a 200-year timescale, sequestration is more sensitive to variations in the size of the recalcitrant fraction than MRTs, particularly once the MRT is greater than 500 years. Thus, if the size of the recalcitrant fraction can be established for a biochar, the precise determination of its MRT – so long as it is greater than approximately 500 years – is not so critical for timescales of a century. However, if the MRT is less than a few hundred years, the establishment of both parameters begins to become important, along with the given MRT of uncharred biomass. This concept is explored further in Figure 3 in a paper by Lehmann *et al.* [51], including investigation of the effect of application rates.

Permanence for any long-term carbon storage project must be confirmed by determining whether the project is continuing to store carbon or when it stops to store carbon and must involve a mechanism to replace

Table 1. Permanence issues by emission reduction or carbon sequestration source.

Project area	Permanence issues
Destruction/alteration of greenhouse gases (e.g., CH_4 from landfills)	Emissions are directly reduced and are nonreversible: highly permanent
Energy use (e.g., increased energy efficiency or renewable fuels)	Less fossil fuel is used, but it does not stop these fuels from being used by another source in the future and producing emissions – emissions are prevented or delayed but atmospheric CO_2 is not directly decreased
Terrestrial carbon stocks	Terrestrial carbon stocks are actually increased, drawing down the stock of CO_2 in the atmosphere, but the stock still cycles as part of the global carbon cycle, leaving potential for its eventual release – relevant timescale determines 'permanence'

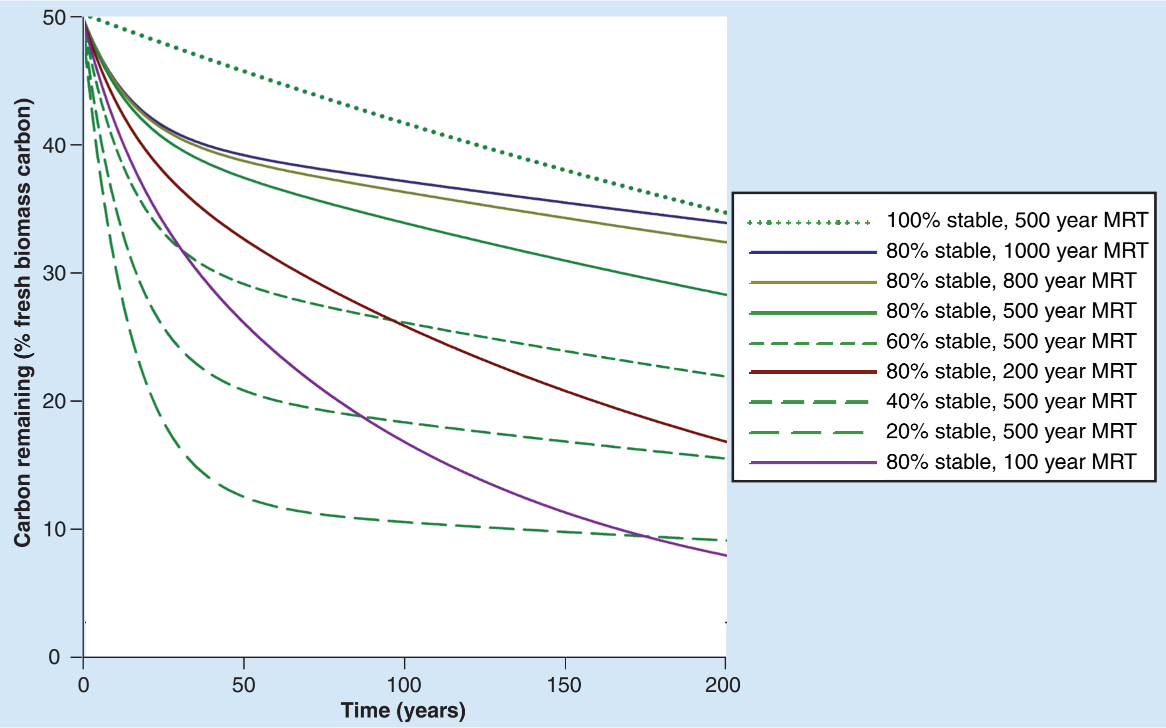

Figure 5. Percentage carbon remaining in biochar over time; varying the stable fraction (with a mean residence time of 500 years) and the mean residence time (with 80% stability).
MRT: Mean residence time.

any eventual releases of stored carbon. Approaches for addressing this issue have included:

- The use of 'buffers' – some credits are never sold, to make up for those that could possibly be lost;
- Substitution – ensuring that if one project fails, another is created to take its place (risk management through a portfolio of different mitigation activities);
- Insurance regimes;
- Using 'tonne–year accounting', where credits are valued based on the number of tonnes sequestered and for how many years they are sequestered [52–55].

The latter two options are applied at the project level, while the first two are applied at a scale where projects are aggregated; for example, forestry projects under the CDM use an approach where the carbon sequestered results in a credit that is considered temporary and expires after a designated period and must be replaced, even if the carbon apparently remains sequestered [28], while land-based offsets in the voluntary carbon market may use any or none of these approaches.

The number of credits delivered in tonne–year accounting for most terrestrial systems is highly sensitive to 'equivalence time' – the number of years of storage that is deemed to constitute 'permanent' sequestration [55]. This high sensitivity to equivalence time occurs when carbon turns over on timescales much faster than 100 years, and where human and natural interferences such as fires or insect outbreaks are difficult to predict. In the case of biochar, this issue is simplified if a significant portion of the biochar will remain stable for much more than 100 years [32] (or other equivalence times that would likely be used). Determining this 'stable fraction' could be sufficient to quantify the effective permanence of carbon storage using tonne–year accounting and an equivalence time of 100 years or more, making a form of tonne–year accounting a viable approach for measuring biochar projects. However, the global warming potentials (GWPs) on which this concept is based are somewhat contested, due to their lack of economic rationale for the 100-year equivalence time and other issues [54,56–60].

If one believes that an increase in carbon storage within a natural system can never be considered permanent on a relevant timescale, then we must consider whether storage for temporary credits, such as the forestry carbon credits in the CDM, is valuable. In order for this to be true, purchasing a temporary credit today that will eventually expire, plus the cost of purchasing a permanent credit at some time in the future would have to cost less than purchasing a permanent credit today, or there would have to be some added value in temporary credits, such as ecological or agronomic benefits. Detractors of temporary credit schemes argue that in order for temporary credits to be replaced with permanent credits, regulatory mechanisms and institutions will have to be in place over very long periods of time, and the social, political and economic uncertainty surrounding these assumptions are too great. However, this is, in essence, true of any regulatory system.

Initial analyses into this question suggest that temporary crediting would be valuable for some carbon-sequestration projects [52,54]. If we consider deep ocean carbon storage, as an analog for biochar, we can extend Herzog *et al.*'s analysis to a biochar system [54]. This comparison is appropriate in that carbon stored in both systems is very slow-cycling, human and natural interventions are unlikely to cause major unexpected loss events, and it is challenging to directly measure the remaining stored carbon over time. Since we would expect the possible carbon loss curves of a given biochar to be approximately similar to the oceanic carbon loss curves in Herzog *et al.*'s analyses, we can predict that biochars with MRTs of between 150 and 575 years could be economically viable in a system where carbon offset prices remain constant, while somewhat greater stability would be necessary for systems where the price of credits rises for a number of years and eventually stabilizes (this scenario is based on the prediction that an alternative nonfossil fuel energy source will cap the costs of abatement).

A compromise approach for biochar projects may be a combined accounting scheme: energy-based reductions from biochar projects are judged under the same shorter crediting period as nonforestry projects, but the terrestrial carbon impact of biochar within the system accrue under longer crediting periods over which its effects last. Any energy-based offsets from an introduced biochar stove would result in permanent credits for the first crediting period (with an option for review and renewal, based on standard re-evaluation procedures), while the emission reductions from baseline due to biochar that are produced over that time period (Figure 2) are designated as temporary credits initially, with a potential to be proved permanent over time. These credits would be reissued and adjusted according to the baseline after each crediting period, regardless of whether the energy-based offsets are renewed. The size of the biochar credits would be expected to grow initially, as their divergence from the baseline biomass scenario would increase over time, so each crediting period would more than replace the credits issued in the previous period (Figure 6; no project renewal). If review of the baseline scenario for the energy-based reductions results in renewal of the biochar project, then the biochar generated from this period would also be counted in future crediting periods (Figure 6; 1 project renewal). This approach accounts for economic and technological baseline uncertainties while allowing for the slower dynamics of natural systems to be accounted for at the same time. While

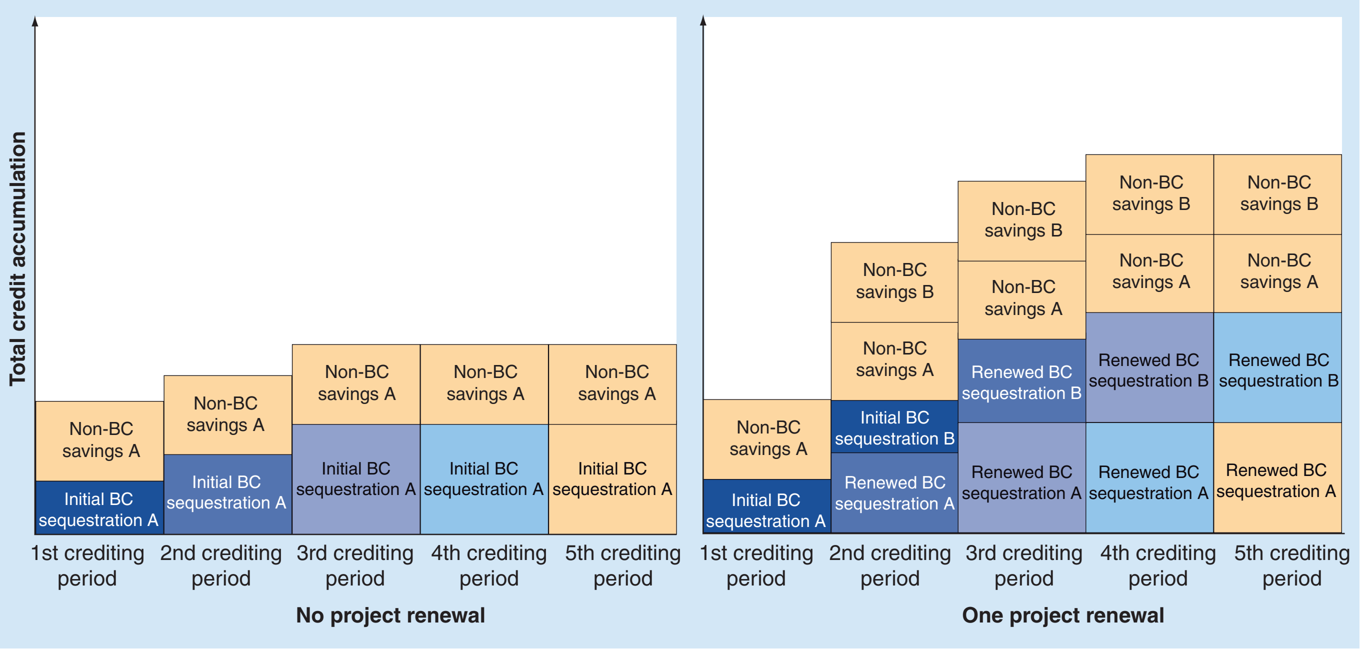

Figure 6. Possible crediting scheme for biochar projects. Orange rectangles represent permanent credits, while blue rectangles represent temporary credits.
BC: Biochar.

scientifically appropriate, temporary credits have proven to be a hurdle for the success of forestry projects in terms of policy and market access. For biochar, it would be scientifically robust for the number of crediting periods to be substantially higher than is currently standard, since its effects would be expected to persist for very long periods of time and it would not be subject to the same uncertainties as other terrestrial carbon projects. After having established their persistence over a designated number of renewal periods, the credits could eventually be designated as permanent. This could allow biochar to succeed where other terrestrial carbon sequestration schemes – such as no-till agriculture or afforestation/reforestation – have struggled to guarantee long-term carbon sequestration.

For biochar projects outside of offsetting schemes, the question of permanence is less critical – the biggest question is whether we are optimally managing terrestrial carbon. For offsetting projects, however, it is critical, because emissions are being released elsewhere – permanently – in the place of the project. Without the driver of **carbon offsetting** finance, biochar projects may be less economically attractive and would rely more heavily on the value of their co-benefits, such as energy production, soil improvement and organic waste management.

Leakage & system drivers

Leakage occurs when a project that reduces emissions within a boundary produces unintended changes elsewhere (i.e., spatially or temporally) that result in higher net emissions than predicted. An example is the situation that occurs when groups in developing countries without Kyoto commitments clear native forests to make way for creditable CDM afforestation and reforestation projects [61]. Within the compliance offset market, these unintended consequences are a problem twice over – first, because of the direct impact they have in the area of leakage and, second, because the supposed reduction was credited against allowed emissions under the carbon trading scheme. These effects can be captured by the use of **life-cycle assessments** (LCAs) or other system analyses, but this requires the consideration of the effects beyond the typical project boundaries, which may be difficult to identify.

Besides acting as a very stable pool of carbon, biochar may interact with the soil and climate system in other ways, which must be investigated when measuring its net impact. The magnitude of biochar loss to the atmosphere as particulate black carbon or its effects on soil N_2O, CH_4 and CO_2 emissions are generally poorly characterized and are an important area for future study before widespread application is advocated. Black carbon particles in the atmosphere are known to increase radiative forcing and, although they have a much shorter MRT than most GHGs, when they settle out of the air, they decrease the albedo of land surfaces, particularly in polar regions [62–64].

Empirical evidence has been provided in which N_2O emissions in biochar-amended soils were reduced in several cases [65–68], but are increased in others, particularly at high moisture contents [65] or following a large addition of nitrogen [67]. Studies have noted variable CH_4 responses, with some decreases [69,70] and other increases [66,68]. This issue could be addressed by current CDM methodology, which allows for direct CH_4 emissions from pyrolysed organic matter to be negated when the volatile-carbon-to-fixed-carbon ratio (as determined by the American Society for Testing and Materials International wood charcoal analysis) is less than or equal to 50% [71]. However, this methodology would not address the potential impacts of CH_4 on existing soil organic matter (SOM). The effect of biochar on native organic matter decomposition to CO_2 is also not fully understood. Some studies have observed increased CO_2 emissions or carbon loss when fresh biochar was added to soils and, thus, suggest that the biochar stimulated the decomposition of existing SOM or fresh residue on the soil surface [46,72,73]. Contrary to these results, Kuzyakov *et al.* found no stimulation of SOM decomposition by biochar [44], while Liang *et al.* found that fresh organic matter was incorporated into aggregates more quickly in soils with high biochar contents, protecting SOM [74]. As a rule, if potential soil emissions were expected to decrease for a given biochar–soil pair, it would be acceptable to ignore them or include them as additional emission reductions if they can be verified; however, if it seems that emissions may be higher upon biochar addition, then it is essential that they be quantified. This could be achieved by establishing a control plot to determine what the baseline emissions would have been, but this approach would be time and cost intensive. Current research is investigating these issues and must continue to improve our understanding of not only the GHG effects of biochar application to soils, but also the mechanisms behind these effects. Once a categorization of emission profiles for different biochar-to-soil-application situations exists, conservative default values could be used to overcome time- and cost-intensive requirements for measurement.

Returning to the biochar cook-stove example, if a decrease in fuel use due to greater fuel efficiency simply allows other groups to burn more wood than before, then the emission reductions could be overestimated.

Key terms

Carbon offsetting: Purchasing the credits generated through greenhouse gas reductions from projects in one place, instead of reducing emissions elsewhere. Compliance markets operate within a capped system, such as the Kyoto Protocol, while the voluntary market operates outside of such a system.

Life-cycle assessment: Method to evaluate the impact of the product from a given system, from its 'cradle to grave'.

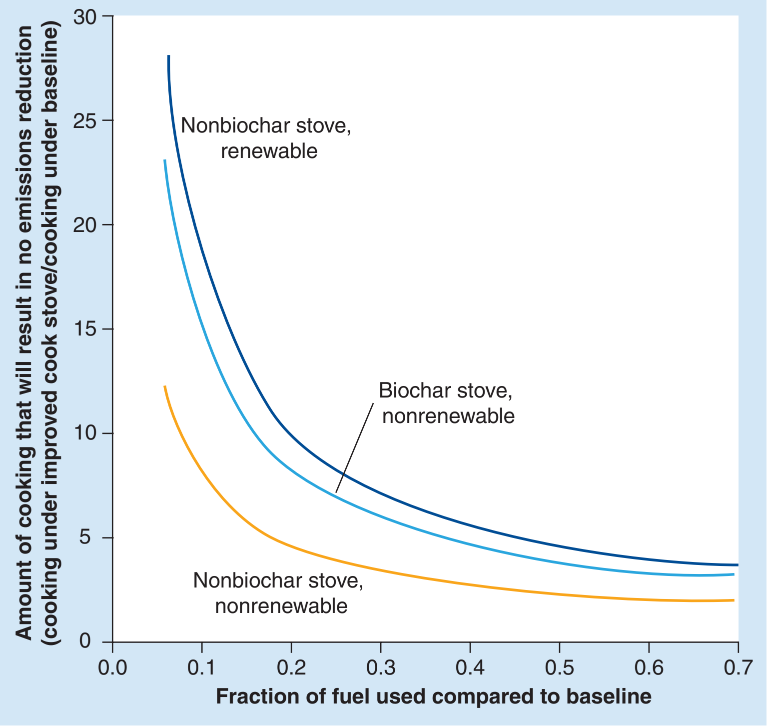

Figure 7. Increase in cooking activity that would increase emissions by an amount equal to the emission reductions from increased efficiency.

A second potential leakage factor is the 'rebound effect' – because the new stoves are more efficient, users may cook more. This factor is investigated in **Figure 7**. Based on the same values as **Figure 4**, the amounts by which cooking activity would have to increase to completely negate the improvements made by a more efficient stove were determined. The renewable biomass biochar stove is not shown here, because increasing stove use would actually increase carbon sequestration.

As seen in **Figure 7**, at relatively high fuel efficiencies, cooking activity would have to increase many times in order to cancel out emission reductions, whether renewable or nonrenewable biomass is being used. Although the net reductions in a nonbiochar-renewable fuel system are lower, such a system is less sensitive to the rebound effect, owing to wider margins in GHG emissions from non-CO_2 gases. These data indicate that the rebound effect would probably not render a cook-stove project's emissions reductions null, because we would expect there to be a limit on how much food would ever be cooked, and so the introduction of a biochar cook stove would be unlikely to act as a driver for increased biomass use. This is an example of 'safe use' – where the driver of the system places a limit on its activity.

If the driver for a system were energy production, as would be the case for an industrial biochar production system, the constant demand for energy would result in a push towards increased biochar production, thus increasing the demand for feedstocks [75]. One of the major critiques of biomass use in biofuels is the direct effects of crop residue removal from soils, which stops the necessary return of carbon and other nutrients to the native system as well as the loss of numerous benefits of residue retention on soils, such as protection from erosion [76,77]. In addition, the indirect effects of the creation of a market for biofuels can act as a driver for other negative processes, including the clearing of a forest for devoted biofuel crops, such as sugar cane production for ethanol, or oil palm production for biodiesel [78]. To avoid these negative impacts, projects should be designed where biomass sources are used explicitly to exclude these effects by using particular kinds of waste streams, which can be considered 'true wastes'.

In the industrial biochar system where switchgrass is used as a feedstock, Roberts *et al.* investigated the impact of including direct and indirect land use changes associated with changing cropland to biofuel plantations and replacing the displaced crops [1]. If this impact was included, it increased the calculated net GHG emissions by over 100%. If an offsetting project had not included this impact, it would have had significant leakage. In this same system, if residential yard waste were to be used as a feedstock, it would be highly unlikely to become a driver for increased production of yard waste. Although it could be argued that the export of nutrients through lawn clippings and raked leaves is undesirable, it seems improbable that, for example, the revenue that the city derives from this alternative waste management system would result in convincing residents to refrain from converting their lawns to more natural systems or deciding to maintain a park's playing field instead of allowing it to revert to forest. Furthermore, the resulting biochar product could be redistributed to citizens for application to their lawns, partially closing this loop, as is done in some municipal composting programs [79]. Returning biochar from true waste feedstocks would allow for a significant portion of carbon and some other nutrients, particularly phosphorous, to be returned to the land, resulting in a 'closed loop' system, whereas they might have ordinarily been lost [21].

We combine these two factors – 'true wastes' and alternate system drivers – to create a conceptual 'safety matrix', predicting which systems would be more sustainable and which would have high potential for unsustainable expansion or significant land use changes **(Table 2)**. The potential for leakage is not, in itself, a problem. It can be predicted using methods such as those investigated above and accounted for using estimates that will result in conservative predictions of emission reductions. It is only when it is neglected that negative consequences occur.

Measurement & verification

We divide approaches to measuring the biochar that is produced in a given system into two broad categories: it could be measured during production and soil application, after which its long-term deviation from the baseline scenario could be predicted (indirect measurement), or it could be measured directly in the soil over a number of years (direct measurement) [21]. Direct measurement is attractive from a scientific point of view because it helps to establish a concrete estimate of the longevity of biochar, but it may be problematic in terms of associated costs and in systems with high spatial heterogeneity of soils or biochar application, requiring the analysis of many soil samples (see Mooney *et al.* for discussion of costs of soil sampling for soil carbon sequestration [80]). Direct measurement may also be challenging in systems with high losses through erosion or leaching. Charcoal has been shown to erode preferentially over other soil components in some systems [81,82]. In addition, in one study in which biochar was added to a Colombian savannah Oxisol, the most significant biochar losses from the system (20–53%) were attributed to runoff and biochar was shown to leach through soils as both dissolved organic matter and, to a lesser extent, particulate organic matter [45]. If the biochar is transported from the system but not lost as CO_2, direct measurement would result in dramatic underestimates of its longevity.

It could be preferable to use indirect measurement of biochar to measure its impact. Since the reduction in CO_2 can be measured as the difference from a baseline scenario where the biomass decays or is burned [21], rather than the increase in soil carbon stocks, whether 100% of the biochar remains in the soil where it is applied may not be a critical question, so long as it can be established that any transport from the system would be likely to decrease the rate of decomposition to CO_2, rather than increase it. We explore this question in Figure 8, considering transport through erosion and leaching to lake and ocean waters, lake and ocean sediments and the atmosphere. From what we know of these zones, we predict that the zone to which biochar would be applied – the top layers of soil – is probably the most conducive zone for organic matter decomposition.

While verifying the amount of biochar present in a soil is feasible [21,83], using this metric for the total biochar storage while ignoring erosion or leaching losses may not be a good way to estimate whether the carbon in the biochar is still sequestered for some systems. Monitoring direct biochar production and using decomposition studies [34,44] could be a more accurate and less expensive predictor, combined with a minimal degree of soil sampling to establish that biochar is being applied to soil and not, for example, being used as fuel. Developing confidence in this approach would be instrumental in maximizing biochar's potential as a carbon-sequestration mechanism and is a research challenge for the future.

Table 2. Safety matrix of feedstock and system drivers for biochar-producing systems.

System driver	Feedstock	
	True waste	Purpose-grown
Cooking energy (safe usage)	Banana leaves in cook stove (low risk)	Biofuel tree plantations for cook stove (medium risk)
Energy production	Yard waste in industrial pyrolysis plant (high risk)	Switchgrass for industrial pyrolysis plant (highest risk)

Based on the principles outlined thus far in this article, we propose that accounting for carbon credits issued for biochar production might be structured around the approach outlined in Figure 1. Measurements of crop yields and GHG emissions from the soil in which biochar is applied are measured using control (untreated) plots and biochar plots. The biochar itself is compared with the baseline scenario of predicted biomass decay or loss by burning in the given environment, based on an indirect measurement of a stable proportion of the carbon fraction and its MRT, through incubations or other predictive measures. This approach focuses on the carbon that is directly sequestered in biochar and would be nested within the broader project assessment, which would also include direct emissions reductions and fossil fuel-displacement or efficiency improvements.

Economics

The economics of biochar systems is a nascent field of research. In particular, the potential income of carbon assets generated by different biochar systems or their different components is not yet fully researched. In essence, the total value of the carbon asset generated by a biochar system would depend on the development and application of baseline and monitoring methodologies or methodology tools (i.e., modules) to capture those value streams. A methodology creates a carbon asset by clarifying approved procedures to determine emission reductions from a project activity over time. Carbon assets can then be used as offsets for means of compliance or for voluntary reasons.

Currently, there are over 120 active and approved CDM methodologies – covering a wide variety of project types and technologies (sectoral scopes); however, none has been approved for biochar so far. A first attempt has been made under the voluntary carbon standard (VCS; a carbon offset standard for the voluntary market) [84]. This submission is a large-scale methodology quantifying the GHG emission reductions from the production and incorporation of biochar into soil in

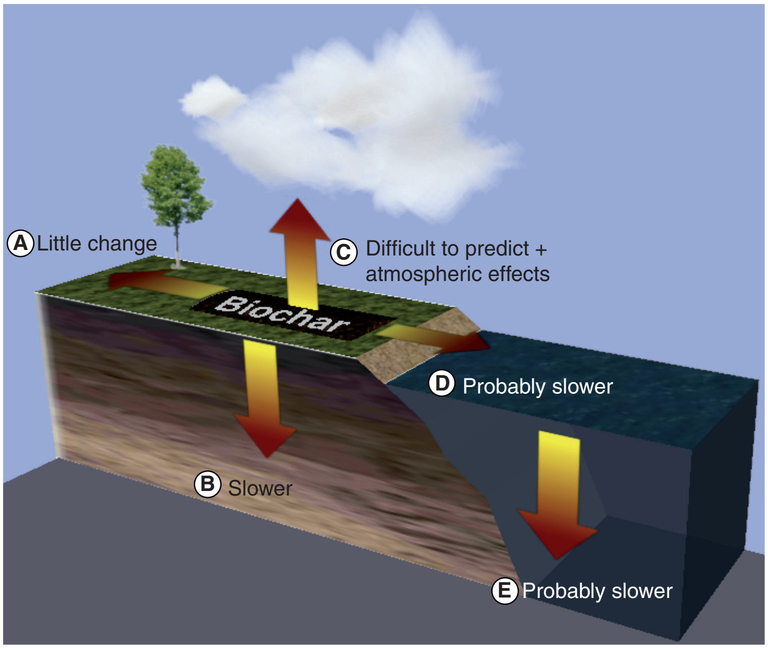

Figure 8. Predicted effect on rate of decomposition after biochar transport, based on rates for nonbiochar organic matter and charcoal. **(A)** Dependant on local environmental conditions. Effect of erosion on carbon sequestration somewhat contested: burial of sediments may slow CO_2 release [93], while breaking of aggregates during transport could lead to SOM decomposition [77]. **(B)** Optimal decomposition tends to occur in top layers of soil and in litter layer; this trend may be somewhat different in regions where moisture is highly limited in top layers of soil [94–96]. **(C)** Black carbon particles have a shorter mean residence time in the atmosphere than GHGs and would be expected to settle out at the Earth's surface relatively quickly, although their radiative forcing and albedo effects upon settling, particularly in polar regions, should still be considered by exploring wind erosion and tranpsort [63–84,203]. **(D)** Complex C and BC cycling in the water column has been studied, but many questions remain [97,98]. In general, anaerobic conditions are not ideal for biochar decomposition [34]. The mean turnover time for DOM in oceans is estimated to range from 60–90 years at the surface to 3700–6000 years in deep waters [99] and particulate bituminous coal has measured lifelines of thousands of years in air-saturated water [100]. **(E)** Due to anaerobic conditions, even oxic BC sediments are found to decompose only over thousands of years [101]. factors such as the oxygen content of the waters or their acidity also play into storage [102,103]. For example, the presence of oxic deep waters that cause mineralization of organic matter in the oceans means that lake sediments may preserve a greater fraction of organic matter [104].

agricultural and forest-management systems, using a biochar production system that is conceptually similar to the industrial system considered in Roberts *et al.* [1]. The first VCS assessment of this methodology is ongoing and the market relevance of this methodology has yet to be seen. An important starting point for any biochar cook-stove methodology would include the gold standard (another carbon offset standard): Indicative Program, Baseline and Monitoring Methodology for Improved Cook-Stoves and Kitchen Regimes [202], and the CDM's energy efficiency measures in thermal applications of nonrenewable biomass [35].

By developing a methodology, a project proponent develops a public good, since once the methodology is approved it can be used by any other project developer as well. Hence, there is no clear first mover incentive for entities proposing methodologies, even more so because costs to develop a new methodology can be substantial. A recent World Bank report looking back on 10 years of carbon finance operations assesses the approximate costs for the development of a new methodology at US$125,000 for both large- and small-scale methodologies, with even higher costs typically incurred for methodologies for afforestation and reforestation projects [203]. According to the same analysis, the approximate time for a new methodology to be developed was 2 years, from inception to approval. Since the methodology costs analyzed above refer to the CDM, which has proven to be a rather lengthy and, hence, costly process, one could hypothesize that the costs for a VCS-type biochar methodology may be slightly lower than the above figure. Still, there are new aspects of biochar systems that need to be methodologically captured and, therefore, costs and resource demands to develop a new biochar methodology (or tools/modules) could still be substantial. Clear incentives to develop broader and more widely accessible methodologies or methodology tools are still missing, at least under the current CDM framework, which considerably hinders innovation. However, recently, the VCS proposed an innovative compensation mechanism for methodology developers by reimbursing part of the incurred costs through a levy on voluntary carbon units (VCUs), the VCS-specific carbon asset. From an economic perspective, this idea seems to be promising and could spur on the development of a biochar-related methodology since biochar assets created under this new methodology would refund the biochar methodology developer.

Up to now, the economics of process inputs and outputs of industrial-scale biochar systems have been analyzed in greater detail (e.g., [1,85]) than the economics of small-scale biochar systems, such as cook stoves at household level, for which such analyses are almost nonexistent. Cost factors covered in the industrial-scale biochar system analyses are for production and collection of feedstock, feedstock transport, possible storage and (pre)-processing of feedstock, costs of the pyrolysis operation itself, biochar transport and the subsequent biochar application to fields. These cost factors are compared with the benefits of selling energy created during the exothermic pyrolysis process, biochar-related cost savings through improved fertilizer use efficiency, and the value of the N and P content of the biochar, as well as the carbon asset generated by the biochar operation. Possible additional revenues can be tipping fees in the case of a biomass waste-to-biochar management scenario. Overall, Roberts *et al.* found that transportation distance has a significant impact on costs [1], which coincides with the findings of McCarl *et al.* [85]. Furthermore, pyrolysis plant fixed and operating costs, as well as energy prices, are important factors for the economic viability of biochar systems on a larger scale. Roberts *et al.* found that the break-even prices were US\$40/tCO_2e where corn stover is used as the pyrolysis feedstock and US\$62/t CO_2e for a switchgrass scenario, but only US\$2/tCO_2e for yard waste [1]. In general, situations where feedstock is available only as decentralized field residue that needs collection and transport seem less economically attractive than scenarios involving more centralized process residues or waste streams that have low transportation requirements.

An area that has not been captured by the current economic analyses of biochar systems from a carbon finance perspective are the costs involved to prepare the necessary documentation to credibly demonstrate the creation of a carbon asset. Under the CDM, this would mean the preparation of a project design document (PDD), including a description of the baseline and monitoring methodology to be used, an analysis of environmental impacts of the proposed project, comments received from local stakeholders and a description of new and additional environmental benefits that the project intends to generate. Official data on actual costs for PDD preparation of CDM projects are somewhat scarce. Costs vary to a great extent depending on the project's complexity (i.e., project size and sectoral scope or technology) as well as the experience of the project entity preparing the PDD. For biochar operations, as a newly emerging project category, PDD costs of US\$20,000–50,000 do not seem to be unrealistic. This does not include the development and approval process of the underlying methodology, which is the basis for a successful PDD completion in the first place.

The preparation of a PDD is followed by what is known as validation and registration of the project. During validation, an independent entity reviews the aforementioned project documentation and provides an opportunity for public comments. The project site is also visited. After that, the validator (or designated operational entity, in CDM terminology) will forward all documentation to the CDM's Executive Board for formal registration [86]. Early experiences from the CDM show that validation and registration can cost between US\$15,000 and US\$25,000 for large-scale CDM operations, with small-scale operations not lagging far behind [203].

Once a project is operational, successful implementation and carbon asset delivery depend on adhering to a predefined monitoring plan. The monitoring plan specifies all variables to be measured over time and the frequency of measurement. Failure to comply with the monitoring plan means that the reported emission reductions may be disputed, possibly resulting in substantial discounting of the carbon asset, which would have negative consequences on the project's cash flow. The monitoring report is the basis for successful verification and certification of the project. After that, 'issuance' can be requested, where ERs are distributed to project participants and proponents as requested. Detailed costs for the latter steps of the process toward the establishment of a carbon asset are difficult to obtain. However, Figure 9 gives an overview of costs per expected tonne of CO_2 e contracted according to different project types within the World Bank's carbon fund portfolio [203]. The differences in unit project costs largely correlate with project size. While initial project development costs have been higher, on an absolute basis, for the industrial gas projects, the unit cost is still very low owing to the volume of expected emission reductions from these projects. In other words, technologies that provide for larger scale projects generate more emission reduction credits, thereby allowing the fixed costs to be spread. For biomass energy, the project development costs are approximately US\$0.5 per expected tonne of CO_2e generated. For forestry operations, the limited data sources available indicate that preparation costs are even higher than for wind energy, that is, above US\$0.8 per expected tonne of CO_2e generated. At the same time, Johnson *et al.* predict a US\$8/tCO_2e cost for their cook stoves, under a conservative (60%) adoption

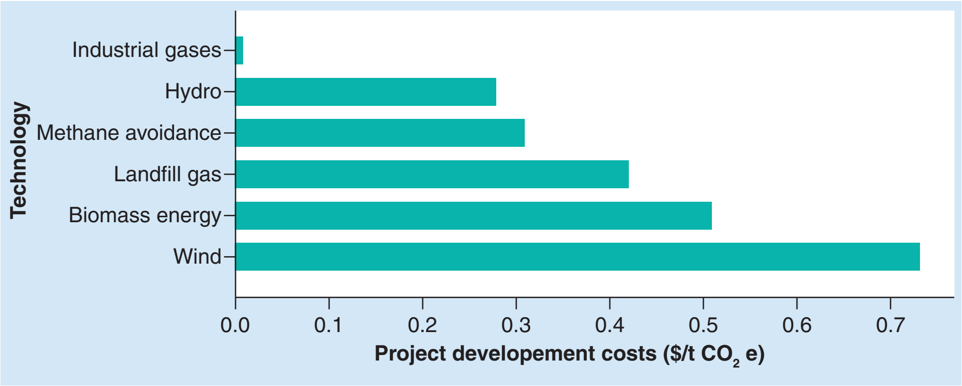

Figure 9. World Bank greenhouse gas-mitigation project development costs by technology (n = 53).
Data adapted from [91].

rate over a 7-year crediting period and including project establishment and monitoring costs, but not including other bureaucratic costs [36]. Exactly where a biochar operation would fit into this cost spectrum is difficult to tell with certainty. Assuming from the above discussion that individual biochar projects, particularly cook-stove applications, would generate fewer ERs as compared with industrial gas projects, project development costs would be greater for biochar. If a biochar cook stove produced greater ERs than another improved cook-stove, we could expect a lower per tCO_2e price; however, if the increased complexity of the system resulted in higher monitoring costs, then prices would increase. At the same time, distinct monitoring advantages for biochar-to-soil applications such as indirect monitoring, as discussed earlier, or mid-infrared spectroscopy, as discussed in Manning and Lopez-Capel [83], indicate that biochar carbon sequestration in soils could be monitored more efficiently compared with other soil or forest sequestration, which would be an argument for lower project development costs in biochar. Thus, one could assume that project development costs for a biochar-to-soil carbon asset would imply costs in the range of US$0.55–0.85 per expected tonne of CO_2e generated, with still higher costs for stove-based biochar projects, at least initially, with costs decreasing over time as the technology is applied more widely. The more carbon value streams a biochar methodology would be able to capture, the lower the unit costs would turn out to be.

Coupling carbon credits with development

Many climate change-mitigating projects are coupled with development goals, as typified by the CDM [201]. It is an obvious synergy to aim for, facilitating the 'leapfrogging' of fossil fuel-based technology and using climate financing to promote development simultaneously with mitigation. Using finance through the carbon market to access biochar-stove technology has the potential to reduce respiratory infections, reduce the impact of fuel gathering on women or improve soil for agricultural production [3]. In that sense, true win–win situations could be created. Indeed, development must be at the core of climate change-mitigation projects that are implemented in the developing world, because manipulating the way some of the poorest people in the world live, solely in order to reduce GHG emissions so that countries and firms in the global north can continue to emit, is clearly unacceptable. This is particularly important for biochar projects, because they may involve altering the stocks and flows of biomass upon which people (and natural systems) depend, or promoting lifestyle changes.

In order for climate change-mitigation projects to achieve sustainable development goals, their design and implementation must include the people who will be involved or affected, whether in a developed or developing country. Indeed, such an approach will probably lead to a more successful project [87]. Unfortunately, even in the short time they have existed, there is already a history of infringement on people's rights in some

Table 3. Offsetting issues, risks and recommendations for biochar systems.

Issue	Risk source (and level)	Recommendations (and cost/difficulty of addressing them)
Baseline establishment	Selecting feedstocks that would result in a lower baseline than project scenario (H)	Careful system design and use of a combined baseline approach (L)
Permanence	False application of 'permanence' to natural carbon cycle; failure to replace temporary credits (M)	Combination of full and temporary credits, based on stable fraction of biochar and its MRT (H)
Measurement and verification	Difficulty quantifying net GHG emissions changes in soil system; loss of biochar from the system through erosion or leaching (H)	Measurement of biochar production, with soil samples to ensure its application, combined with full life cycle assessment and further development of field research to allow for conservative assumptions or measurement methodologies regarding non-CO_2 gases (H)
Leakage	Failure to account for direct and indirect land-use change effects; poor estimate of fraction of nonrenewable biomass; rebound effect (M)	Full life cycle assessments; conservative estimates of nonrenewable biomass fraction; measurement and estimation of rebound effect; system design focusing on 'true wastes' and 'safe usages' (M)
Additionality	Co-benefits of biochar beyond carbon could become enough to drive biochar system development alone; biochar technology becomes commonplace (L)	Use of CDM additionality tool; monitoring trends of implementation of biochar systems without carbon offset financing or changes in the barriers and current practices (L)
Economics	Project development costs well characterized but may be relatively high; low incentives for methodology development (N/A)	If more climate-related carbon value streams are captured, project costs will be reduced; providing incentives for methodology developers (N/A)
Development	Interference with local and indigenous peoples' ways of life, ecosystem manipulation (M)	Place development before carbon reductions; use stakeholder consultation (L)

CDM: Clean Development Mechanism; H: High; L: Low; M: Medium; MRT: Mean residence time; N/A: Not applicable.

offsetting projects, such as the imposition of carbon-reducing projects on indigenous peoples without their consultation or involvement in the design and implementation [88,89]. For example, Sutter and Parreño assessed 16 CDM projects and found that, while 72% of the total ERs were likely to be real and measurable, less than 1% of the predicted sustainable development impacts were realized [90]. The implementation of any biochar project in developing countries must be viewed only as a stepping-stone along a self-determined path of development, and must not constrain people to low-carbon technology.

Conclusion

Developing biochar projects to mitigate climate change and their associated methodologies is a complex undertaking that requires consideration of a broad suite of issues, a number of which are summarized in Table 3, along with the risks and recommendations associated with each. Moving forward, the most pressing issue is the development of robust methodologies for measurement and prediction of biochar stability, based on the concepts of a stable fraction and permanence developed in this article, in order to establish a robust methodology for quantification (Figure 1). The effective permanence

Executive summary

Biochar projects & carbon markets

- Biochar is a carbon-rich organic material that is produced using pyrolysis and could be applied in systems to manage carbon and possibly other greenhouse gas reductions.
- Biochar projects could be applied as a stand-alone climate change mitigation approach or as a means to generate carbon offsets, but are not widely applied as either to date.

Additionality & baseline establishment

- Biochar systems could reduce greenhouse gases in a number of diverse ways, including stabilizing biomass and replacing fossil fuels. Accounting for biomass carbon impacts using a longer crediting period than for energy impacts may best capture these differences.
- Using the business-as-usual decay or growth of the feedstock biomass as the baseline scenario is a way to establish whether producing biochar is a good choice for biomass management.
- In a pyrolysis bioenergy system where renewable biomass is used, total emission reductions would increase as more fuel is used, while total emission reductions from conventional bioenergy systems would decrease.

Permanence

- Biochars may have mean residence times (MRTs) of over 1000 years, but may be accounted for more appropriately as having a recalcitrant and a labile fraction (e.g., over 60% of carbon in biochar with an 80% stable fraction that has an MRT of 500 years will persist after 150 years). In this case, biochar stability on a 100-year timescale is more sensitive to changes in the recalcitrant fraction than to changes in the MRT, once MRT is greater than around 500 years, indicating that determination of the proportion of the stable fraction may be an important focus of future research.
- Biochar remains part of the global carbon cycle. Scientifically, considering its carbon sequestration properties, temporary credits seem to be appropriate for the time being, but this approach is a challenge for policy and market access. This may be overcome owing to its extremely long MRT, making it effectively permanent on short as well as even centennial timescales.

Leakage & system drivers

- Further characterization of indirect impacts of biochar on soil emissions of N_2O, CH_4 and CO_2 is an important area for future research.
- Although the 'rebound effect' could be a source of leakage in household biochar systems, household-level cooking is likely a 'safe system driver', as compared with energy production for profit.
- Explicitly designing a biochar system around the use of 'true wastes' as a feedstock can minimize unwanted land-use impacts, and combining this with safe system drivers could minimize leakage.

Measurement & verification

- Transport of biochar from the system after application to soil will make direct measurement problematic, but biochar is likely to be applied in the optimum location for decomposition, and its transport out of the system would be expected to decrease or maintain its rate of decomposition in many scenarios.
- Direct measurement of biochar in soils seems attractive due to its apparent transparency, but indirect measurements may be sufficient and have relatively lower costs.

Economics

- Biochar projects are relatively new and there are currently few comprehensive economic analyses.
- The development and establishment of new methodologies, project design, validation, registration and monitoring would be expected to be rather expensive for biochar projects, perhaps similar to or even higher than biomass energy project costs.
- Biochar may be able to reduce project costs by capturing a number of climate-related carbon value streams.

Coupling carbon credits with development

- Any biochar project must be developed with the involvement of the communities where the project will be implemented.
- Development must be considered before carbon credits in all projects, but particularly in developing countries, since the global north bears the majority of responsibility for the stock of greenhouse gases in the atmosphere.

and value of carbon assets from biochar systems must be derived through careful drawing of baselines, wide system boundaries in order to minimize leakage and focus on 'safe systems' from the outset. Ideally, this may be achieved by designing systems based around 'safe-usage' system drivers and 'true-waste' feedstocks, with human rights as the primary consideration for any development-based projects.

Future perspective

Carbon offsets are a fast-developing field, within which biochar systems are quickly evolving. Biochar was barely on the global radar 5 years ago but today it has evolved into a global phenomenon, eliciting attention from figures ranging from James Lovelock [91] to Al Gore [92]. At this pace, it could gain considerable prominence by 2020, with on-the-ground implementation of a wide range of biochar-producing systems and further developments in our understanding of its interactions with the soil and its net impact on GHGs. At the same time, while many aspects of biochar position it to be an exciting component of an overall climate change-mitigation strategy, a number of important questions remain, and it is essential that critical issues, such as the direct impacts of variable biochar properties on diverse soil types, are evaluated and controlled as such projects become more widely implemented, and that the pitfalls associated with many biofuel systems are avoided. We might hope to see the development of a biochar characterization rubric and a code of best practice completed within the decade, allowing for a safe and regulated implementation of biochar systems.

Carbon markets have proved volatile over the past decade, and their dynamics will certainly affect the degree to which biochar systems are included in carbon offsetting mechanisms. While recommendations push for increasing regulation of GHGs, the inclusion of offsets in future international climate change agreements is not absolutely guaranteed. However, since climate change will certainly continue to be a major global issue, the existence of voluntary carbon markets and other sub-international carbon-offsetting systems will probably provide a platform for continued offsetting projects. Increasing public awareness will probably lead to more stringent regulation of offset projects in the future, as well as further emphasis on projects that have additional value beyond GHG mitigation, such as the potential agronomic benefits associated with biochar.

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